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Benchmarking Electrical Loss in Rectangular Metallic Waveguide at Submillimeter Wavelengths

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Abstract—A series of documentary standards has recently been published (the IEEE 1785 series) that provides specification details for rectangular metallic waveguides used at frequencies from 110 GHz to at least 3.3 THz. This includes values of electrical loss (both reflection and transmission) for these waveguides. However, the values specified in these standards are based on calculated (i.e. modelled) performance and not measured values for real waveguide devices. This paper presents measured values of loss for commercially available waveguides in this frequency range. A comparison is given between the standardized values and values obtained from measurements made under precision laboratory conditions.

Keywords—rectangular metallic waveguide; submillimeter waveguides; terahertz waveguides; electrical loss; terahertz measurements

I. INTRODUCTION

Rectangular metallic waveguides are used extensively at millimeter and submillimeter wavelengths as an efficient means of transporting electromagnetic energy between electronic components, circuits and systems. Their relatively low loss means that signals can be transported over relatively long distances. These waveguides also provide well-defined reference planes for making measurements at these frequencies and, as such, are found on measuring instruments such as Vector Network Analyzers (VNAs) operating at these frequencies (i.e. from 0.1 THz to 1 THz and beyond) [1].

The use of these waveguides, along with the rapid increase in exploitation of the millimeter and submillimeter frequency ranges, has driven the need for international documentary standards to define the geometries involved with these waveguides. This need has recently been addressed by the publication of three new IEEE standards [2-4] defining these types of waveguide.

These standards include values of electrical loss (for both reflection and transmission) that can be expected for such waveguides operating at these frequencies. However, the values of loss given in the standards are based entirely on modelled (i.e. calculated) values, due to imperfections in the waveguide – e.g. dimensional tolerances of the waveguide and the associated alignment mechanisms (i.e. flanges) are used to calculate reflection loss, and, the finite conductivity (i.e. non-zero resistivity) of the metal used for the waveguide walls is used to

calculate transmission loss. The standards do not contain any measured values of loss to substantiate these calculated values.

This paper presents values of measured loss – both reflection and transmission loss – for a range of commercially available waveguides. These measured values indicate the current state-of-the-art for realized waveguides at these frequencies. Measurements were made using a VNA configured for waveguide measurements from 500 GHz to 750 GHz using WM-380 waveguide test ports [2]. Measurements were made of several straight sections of precision, pristine, waveguide ranging in length from 1" to 5". (1" \equiv 25.4 mm.)

II. MEASUREMENT DETAILS

A Keysight Technologies N5247A PNA-X VNA fitted with VDI WM-380 (500 GHz to 750 GHz) Extender Heads was used as the measurement instrumentation. Measurements were made from 500 GHz to 750 GHz at 801 equally spaced frequency points (i.e. every 312.5 MHz). The Intermediate Frequency (IF) bandwidth of the VNA was set to 100 Hz.

Two methods of calibration are available for NPL's WM-380 VNA system: (i) a custom design TRL (Thru/Reflect/Line) technique [5]; (ii) a conventional SOLT (Short/Offset-short/Load/Thru) technique. The custom design TRL technique employs $\frac{3}{4}$ -wave Line standards to provide full calibration coverage across this waveguide band. The standards used for this type of calibration are the UK's primary national reference standards, which provide traceability to the basic quantities of the International System (SI) of units – i.e. the meter, second, etc [6]. This ensures that the measurements are very reliable and represent the current state-of-the-art, in terms of measurement accuracy. The TRL technique is used to verify performance of the conventional SOLT technique. The SOLT technique is used on a routine basis – e.g. for customer measurements, research investigations, etc. The TRL technique is used only when direct traceability is required for the measurements. On this occasion, the SOLT technique was used to calibrate the VNA using a commercially available calibration kit supplied by VDI.

Three waveguide sections of length 1", 2" and 2" were used for the investigation. A photograph of these waveguide sections is shown in Figure 1. These sections were used in combination to provide nominal lengths of 1", 2", 3", 4" and 5" as the five

lines under test (LUTs) – i.e. the 3" LUT was realized by joining together the 1" and 2" sections; the 4" LUT was realized by joining together the 2" and 2" sections; the 5" LUT was realized by joining together the 1", 2" and 2" sections.

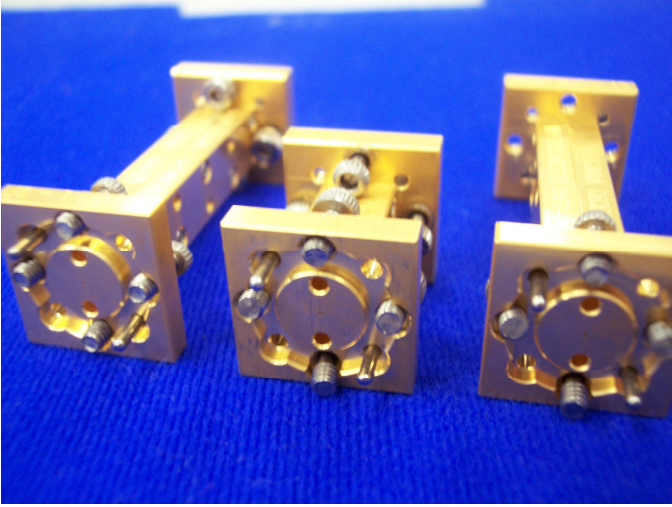


Fig 1: Photograph showing the three waveguide sections used during this investigation

III. RESULTS

Figure 2 shows the measured reflection coefficients (in dB) for the five LUTs. The worst case observed reflection coefficient is approximately -15 dB. The average reflection coefficient for all LUTs at all frequencies is approximately -30 dB. This is considered typical for waveguide at these frequencies. For example, reflection coefficients ranging from -26 dB to -31 dB are given in [3] for the new state-of-the-art waveguide interfaces also described in [3]. There will also be a reflection caused by imperfections in the aperture size and shape [2]. All these effects are described in [4].

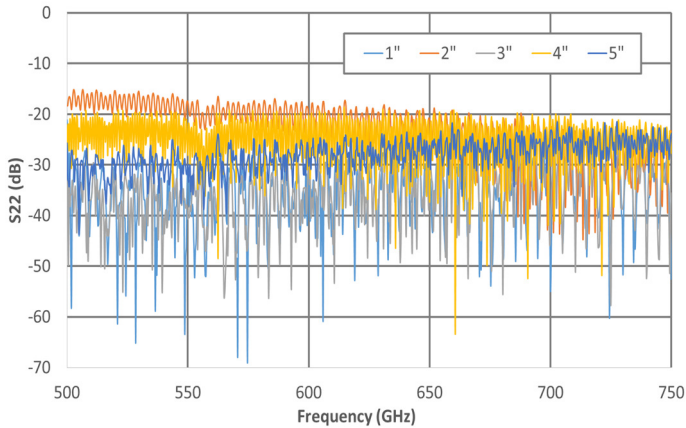


Fig 2: Measured reflection coefficients for the five LUTs

Figure 3 shows the measured transmission coefficients (in dB) for the five LUTs. The dip in transmission at around 557 GHz corresponds to attenuation due to atmospheric water vapor [7, 8]. This is caused by water vapor in the air filling the LUTs.

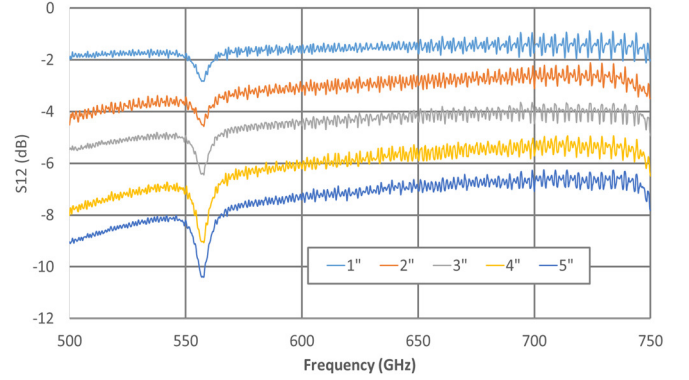


Fig 3: Measured transmission coefficients for the five LUTs

IV. DISCUSSION

The transmission coefficient measurements shown in Figure 3 can be converted to values of loss per unit length by dividing the transmission coefficient values by the length of each LUT. This is shown in Figure 4, where the loss per unit length for each LUT is expressed in dB/cm.

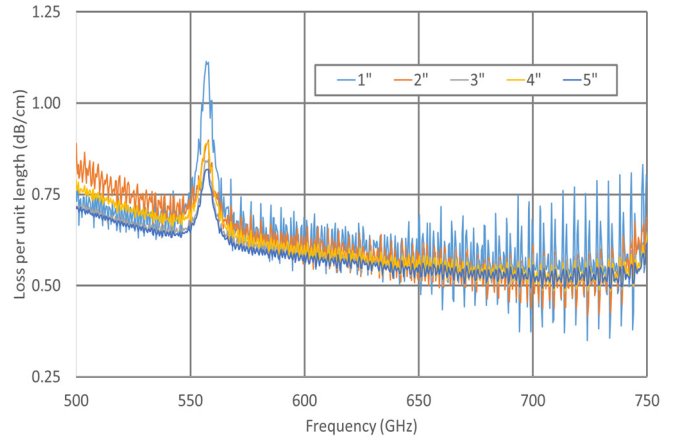


Fig 4: Loss per unit length for the five LUTs

Figure 4 shows that, at each frequency, the values of loss per unit length derived for each LUT are quite similar. This suggests it is appropriate to consider an underlying single value of loss, at each frequency, for this type of waveguide. The values of loss per unit length can therefore be further summarized by calculating a mean value of loss per unit length, $\bar{\alpha}$, at each frequency, using equation (1):

$$\bar{\alpha} = \frac{1}{n} \sum_{i=1}^n \alpha_i \quad (1)$$

where α_i ($i = 1, \dots, n$) are the values of loss per unit length, for the LUTs at each frequency. In our case, since there are five LUTs, $n = 5$. In addition, the uncertainty in the calculated mean value can be evaluated using equations (2) and (3):

$$U(\alpha)_{95\%} = 1.96 \sqrt{\frac{n-1}{n-3}} s(\bar{\alpha}) \quad (2)$$

where:

$$s(\bar{\alpha}) = \sqrt{\frac{\sum_{i=1}^n (\alpha_i - \bar{\alpha})^2}{n(n-1)}} \quad (3)$$

$U(\alpha)_{95\%}$ is the expanded uncertainty in α corresponding to a 95% coverage interval for α , assuming that a scaled and shifted t -distribution with $(n-1)$ degrees of freedom can be used to characterize the uncertainty in α [9].

Figure 5 shows the calculated mean measured loss per unit length along with the associated expanded uncertainty (expressed as a 95% coverage interval), at each frequency.

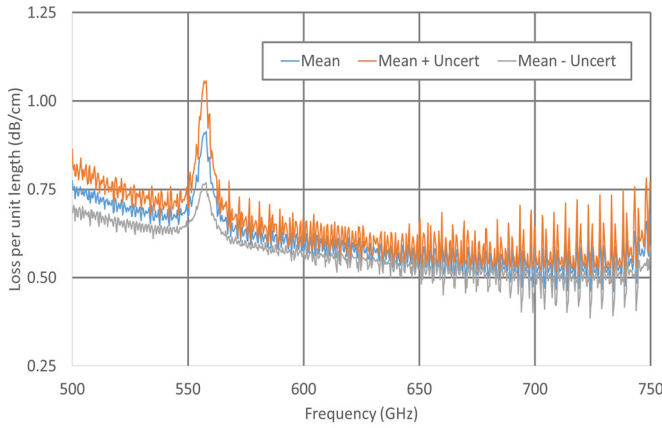


Fig 5: Calculated mean measured loss per unit length and associated uncertainty (as a 95% coverage interval)

Part 1 of the new IEEE standard for metallic waveguides for use above 110 GHz [2] gives modelled values of loss per unit length (also in dB/cm) for waveguides made from different materials (i.e. gold, coin silver and copper). Figure 6 shows the modelled loss per unit length, based on [2], assuming the waveguide material to be either gold (with assumed resistivity of 22.0 nΩ.m), coin silver (with assumed resistivity of 20.3 nΩ.m) or copper (with assumed resistivity of 17.1 nΩ.m).

Comparing the values of loss per unit length based on measurements (shown in Figure 5) with the modelled values shown in Figure 6, it is clear that the values based on

measurements indicate more loss than the values produced by the model. This is also shown in Table 1, which lists the mean measured values, with associated uncertainty, along with modelled values (assuming the waveguide is made of gold), at selected frequencies.

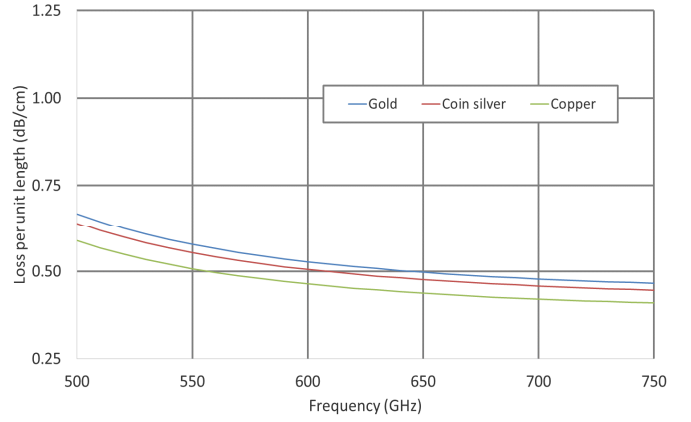


Fig 6: Modelled loss per unit length of waveguides constructed of either gold, coin silver or copper

TABLE I
MODELLED AND MEASURED VALUES OF WAVEGUIDE LOSS PER UNIT LENGTH

Frequency (GHz)	Loss per unit length (dB/cm)		
	Modelled values (gold)	Measured values	
		Mean	Uncertainty
500	0.669	0.775	0.089
550	0.578	0.671	0.028
600	0.528	0.611	0.029
650	0.497	0.587	0.063
700	0.478	0.594	0.049
750	0.466	0.674	0.082

The discrepancy between measured and modelled values of loss per unit length could be due to the reflection losses in the measurements (due to imperfect flanges and waveguide dimensions) that are not present in the modelled values. However, the measured reflections shown in Figure 2 indicate that these waveguides are quite well-matched (for this range of frequencies) and so the impact of reflection loss on transmission loss will be small. A more likely source of the discrepancy between measured and modelled values is due to surface effects – i.e. the roughness of the surface of the waveguide walls, and, the actual resistivity of the metal that comprises the waveguide walls. (Note that the modelled values of loss are calculated assuming classical skin effect and perfectly smooth waveguide walls [2].)

Figure 7 shows modelled values of loss per unit length, assuming the resistivity of the waveguide walls is $28 \text{ n}\Omega\cdot\text{m}$, along with the mean measured values shown previously in Figure 5. The two sets of values show good agreement (apart from the attenuation caused by atmospheric water vapour at around 557 GHz), indicating that the effective resistivity of the waveguide walls (caused by a combination of surface effects – i.e. surface roughness and the actual resistivity of the waveguide walls) is of the order of $28 \text{ n}\Omega\cdot\text{m}$, which is significantly higher than the value of $22 \text{ n}\Omega\cdot\text{m}$ used for gold in [2].

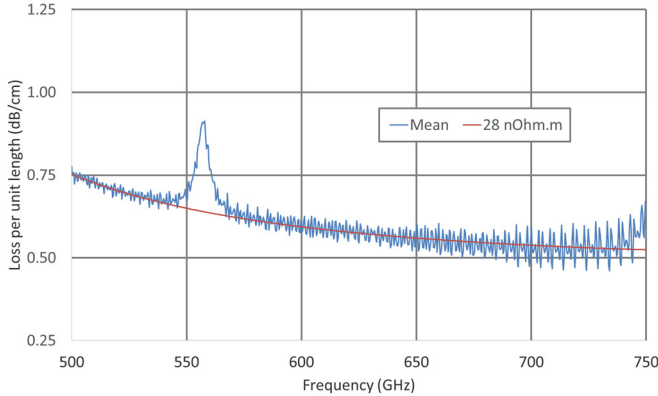


Fig 7: Mean measured loss per unit length and modelled loss per unit length assuming a waveguide resistivity of $28 \text{ n}\Omega\cdot\text{m}$

V. CONCLUSIONS

This paper has described an investigation into the loss of rectangular metallic waveguides at submillimeter wavelengths – in particular, WM-380 waveguide operating from 500 GHz to 750 GHz. The paper has compared calculated values given recently in the literature [2] with values obtained from a series of measurements of sections of commercially available waveguide (manufactured by VDI). The values in [2] are based on a simple theoretical model, assuming: classical skin effect; the waveguide walls are perfectly smooth; and, the waveguide aperture is of nominal dimensions.

For the reflection measurements, generally low values of reflection have been observed for all five LUTs. The worst case reflection coefficient was approximately -15 dB. The average reflection coefficient was approximately -30 dB. These values are comparable with values suggested in the new IEEE standards [2-4].

For the transmission measurements, generally high values of transmission have been observed, for all five LUTs, proportional to the length of each LUT. When these transmission coefficient values were converted to the equivalent loss per unit length, all lines exhibited a similar amount of loss per unit length. However, when these measured loss per unit length values were compared with modelled values given in [2] (where the waveguide conductors are assumed to be made either of gold, coin silver or copper), the measured loss was found to be consistently higher than the values predicted by the model. This type of behavior has been observed previously at millimeter

wavelengths, where it was related to the surface roughness of the conductors used for the waveguide walls (see, for example, [10-11]). In addition, the actual resistivity of the conductors used for the waveguide walls is expected to be higher than the values given in [2], which are derived from values given in tables of physical data [12]. This is because values specified in such tables refer to bulk material samples. These values are often different from actual values for the same material that has been subjected to machining and electroplating, as is often the case during the manufacturing process for high frequency transmission lines, as noted in [13].

Finally, it is expected that the trends observed in this paper for waveguide operating from 500 GHz to 750 GHz will also be found for waveguides operating at other frequencies in the submillimeter-wave band. This implies that the electrical loss data given in the new IEEE standards [2-4] can be used as a benchmark. However, transmission loss of real waveguides used at submillimeter wavelengths is expected to be higher than that given in the IEEE standards.

ACKNOWLEDGMENT

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REFERENCES

- [1] T W Crowe, B Foley, S Durant, K Hui, Y Duan, J L Hesler, "VNA frequency extenders to 1.1 THz," 36th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz), 2011.
- [2] IEEE Std 1785.1-2012: "IEEE Standard for Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above—Part 1: Frequency Bands and Waveguide Dimensions".
- [3] IEEE Std 1785.2-2016: "IEEE Standard for Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above—Part 2: Waveguide Interfaces".
- [4] IEEE Std 1785.3-2016: "IEEE Recommended Practice for Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above—Part 3: Recommendations for Performance and Uncertainty Specifications".
- [5] N M Ridler, "Choosing line lengths for calibrating waveguide vector network analysers at millimetre and sub-millimetre wavelengths", *NPL Report TQE 5*, National Physical Laboratory, UK, March 2009.
- [6] SI Brochure: The International System of Units (SI) [8th edition, 2006; updated in 2014]. <http://www.bipm.org/en/publications/si-brochure/>.
- [7] J Sun, F Hu, S Lucyszyn, "Predicting Atmospheric Attenuation Under Pristine Conditions Between 0.1 and 100 THz", *IEEE Access*, Vol 4, pp 9377-9399, 2016.
- [8] Recommendation ITU-R P.676-11, "Attenuation by atmospheric gases", International Telecommunications Union, September 2016.
- [9] JCGM 101:2008, "Evaluation of measurement data – Supplement 1 to the "Guide to the expression of uncertainty in measurement" – Propagation of distributions using a Monte Carlo method".
- [10] F J Tischer, "Experimental attenuation of rectangular waveguides at millimeter wavelengths", *IEEE Trans-MTT*, Vol 27, No 1, pp 31-37, 1979.
- [11] F J Tischer, "Excess conduction losses at millimeter wavelengths." *IEEE Trans MTT*, Vol 24, No 11, pp 853-858, 1976.
- [12] "Kaye and Laby – tables of physical and chemical constants", available online at: www.kayelaby.npl.co.uk.
- [13] B O Weinschel, "Errors in coaxial air line standards due to skin effect", *Microwave Journal*, Vol 33, pp 131–43, 1990.